

# OPTIMIZATION OF DECENTRALIZED HYBRID MICROGRIDS USING AI-DRIVEN SMART CONTROLLERS FOR RURAL ELECTRIFICATION IN PAKISTAN

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## Abstract

Pakistan faces a persistent rural electrification crisis, with ~23% of its population (~40 million people) lacking reliable grid access due to economic unviability of grid extension in low-density, geographically challenging areas, compounded by high transmission losses (up to 65% in some DISCOs) and circular debt. Decentralized hybrid microgrids (solar PV, wind, diesel/biomass gensets, battery storage) offer a viable pathway to energy access, yet their performance is constrained by intermittent renewables, load variability, battery degradation, and suboptimal dispatch. This review examines AI-driven smart controllers encompassing deep reinforcement learning (DRL), adaptive neuro-fuzzy inference systems (ANFIS), convolutional/recurrent neural networks (CNN/LSTM), genetic algorithms, particle swarm optimization, and hybrid metaheuristics for real-time optimization of microgrid operation in rural Pakistani contexts. Key applications include predictive load/PV forecasting, dynamic energy management (optimal unit commitment, battery scheduling, demand response), multi-objective optimization (cost minimization, reliability maximization, emissions reduction), and uncertainty handling (weather/load stochasticity). Case studies and simulations demonstrate 15–40% reductions in levelized cost of energy (LCOE), 20–50% improvements in renewable penetration, extended battery lifespan via depth-of-discharge management, and enhanced resilience during blackouts or extreme weather. Challenges high initial costs, data scarcity, computational demands in remote settings, and limited local technical capacity are addressed through edge computing, transfer learning, low-cost IoT sensors, and community-based models. AI-optimized hybrid microgrids emerge as a scalable, resilient solution for achieving SDG 7 (affordable, clean energy) and supporting rural socio-economic development in energy-poor regions of Pakistan.

Introduction

1. Historical Context and the Crisis of Centralization

The energy sector in Pakistan is currently navigating a period of profound transition, defined by a critical disconnect between national generation capacity and the functional availability of electricity for the peripheral population (Wenlong et al., 2023). As of the early 2020s, the country boasts a total installed capacity exceeding 41,000 MW, yet it remains incapable of providing stable, grid-based power to approximately 23% of its citizens (National Electric Power Regulatory Authority [NEPRA], 2023). This systemic failure has left over 40 million people in total energy poverty, primarily in rural areas where the extension of the national grid is deemed economically unviable due to low population density and challenging geographic terrains (Urpelainen & Ahmad, 2019). The crisis is compounded by a mounting circular debt and significant aggregate technical and commercial losses, which in some distribution companies reach as high as 65% (Kessides, 2020).

Historically, the national energy strategy was characterized by short-term planning and an over-reliance on imported fossil fuels. In the 1990s, policies prioritized rapid generation capacity expansion through Independent Power Producers

(IPPs), largely neglecting the potential for renewable energy integration or infrastructure efficiency (Valasai et al., 2017). This created a path-dependent reliance on oil and liquefied natural gas (LNG), making the economy highly vulnerable to global price volatility. In 2022, for instance, the national oil bill surged by 96%, reaching 17.03 billion USD, which depleted foreign reserves and fueled inflation (PBOs, 2022). The World Bank's Regulatory Indicators for Sustainable Energy (RISE) reflect this historical neglect, awarding Pakistan a score of only 28 out of 100, highlighting massive gaps in policy, regulation, and financing (World Bank, 2020).

The shift toward a more sustainable framework began in the late 2010s with the introduction of the Alternative and Renewable Energy (ARE) Policy (2019) and the National Energy Efficiency and Conservation Plan (2020-25). These policies aim to increase the share of renewable energy in the total mix to 30% by 2030, leveraging Pakistan's indigenous resources (Government of Pakistan, 2019). However, achieving these targets requires a departure from the traditional centralized model toward decentralized hybrid microgrids, which can operate autonomously and provide resilient, localized energy solutions (Shakeel et al., 2016).

Table 1. Policy Milestones and Objectives for Pakistan's Energy Sector

Policy Milestone	Primary Objective	Key Limitations
Energy Policy (1994)	Expand generation through IPPs	Neglected renewables and efficiency
Renewable Energy Policy (2006)	Introduce incentives for VRE	Inconsistent implementation
ARE Policy (2019)	30% RE share by 2030	Institutional and financial barriers
NEPRA Microgrid Regs (2022)	Enable decentralized providers	Market uncertainty and risk perception

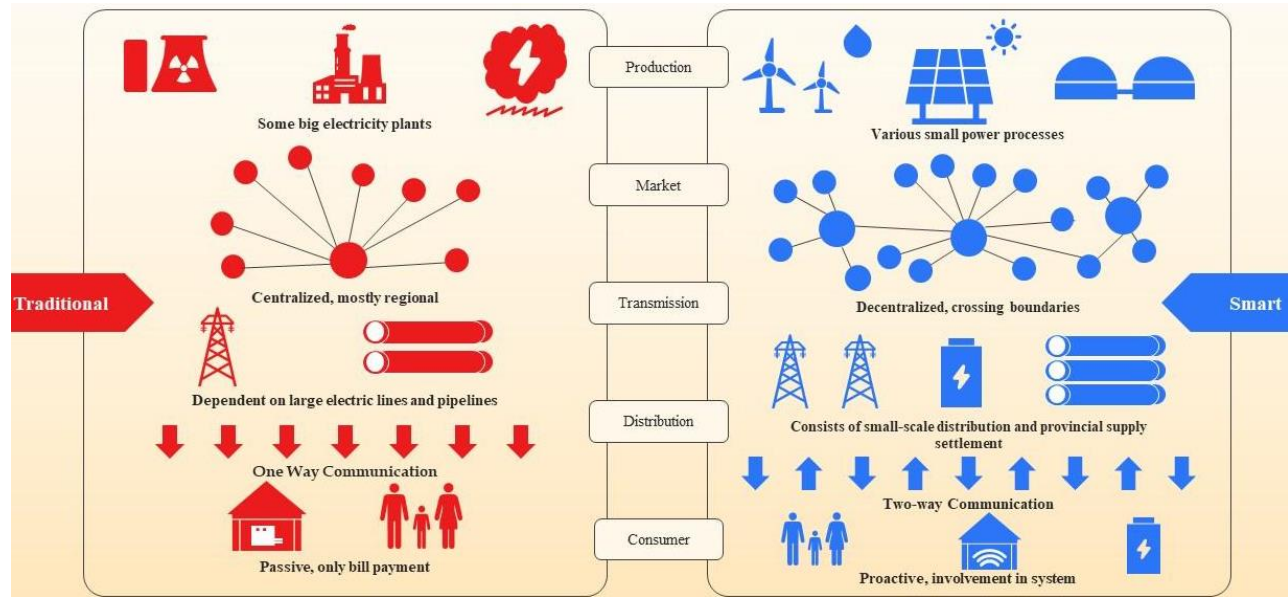


Figure 1: Centralized Grid vs Decentralized Microgrid Electrification Model

2. Renewable Energy Potential and Regional Synergy

Pakistan’s geographic diversity offers a unique advantage for the development of hybrid microgrids. The country is situated in the global solar belt, receiving an average of 8 to 10 hours of sunlight daily, with 95%

of its landmass suitable for solar exploitation (Baloch et al., 2021). Concurrently, the coastal belts of Sindh and Balochistan possess vast wind energy potential, while the northern regions of Gilgit-Baltistan and Khyber Pakhtunkhwa are rich in micro-hydropower resources (Baloch et al., 2023). The limitations of centralized grid infrastructure have intensified the rural electrification challenge in Pakistan. Figure 1 contrasts the traditional centralized electricity delivery system with decentralized hybrid microgrid architectures capable of serving remote communities.

2.1 Solar and Wind Resource Distribution

The province of Balochistan is particularly well-suited for solar energy, receiving between 5 and 7 kWh/m<sup>2</sup> of daily solar radiation (Arif et al., 2020). Solar energy is highly modular, making it the preferred choice for small-scale residential applications and off-grid community projects. However, solar energy remains undependable as a

standalone source due to its diurnal cycle and sensitivity to cloud cover, necessitating robust storage or hybridization (Irfan et al., 2021).

Wind energy complements solar profiles in the coastal regions of Sindh and Balochistan. The wind corridor in Sindh, specifically in areas like Jhimpir and Gharo, has an estimated commercially exploitable potential of 120 GW (Khahro et al., 2014). Average wind speeds in these regions range from 7 to 8 m/s, categorized as International Electrotechnical Commission (IEC) Class 2 and 3.

The combined output of a hybrid solar-wind microgrid can be represented as:

$$P_{total}(t) = P_{solar}(t) + P_{wind}(t)$$

where solar generation is primarily driven by irradiance  $G(t)$ :

$$P_{solar}(t) = \eta AG(t)$$

and wind power depends on wind speed  $v(t)$ :

$$P_{wind}(t) = \begin{cases} \frac{1}{2} \rho A C_p v(t)^3, & v_{ci} \leq v(t) \leq v_r \\ P_r, & v_r < v(t) \leq v_{co} \\ 0, & \text{otherwise} \end{cases}$$

where  $\eta$  is panel efficiency,  $A$  is area,  $\rho$  is air density, and  $C_p$  is the power coefficient.

Hybridizing solar and wind thus smooths intermittency, as wind generation often peaks at night or during monsoon periods when solar output is minimal (Naeem et al., 2020), improving

overall system reliability and reducing storage dependence.

### 2.2 Biomass and Small-Scale Hydropower

In rural Punjab and Sindh, biomass energy derived from agricultural residues and animal waste provides a sustainable baseline for microgrids. Meanwhile, in the mountainous north, micro-hydropower plants (MHPPs) utilize glacial streams to provide consistent power. Projects in villages like Assumber have demonstrated that combining micro-hydro with biomass gensets and battery storage can meet 100% of a community's energy and water heating needs (Ali, 2025).

The combined hybrid generation in such systems can be expressed as:

$$P_{\text{total}}(t) = P_{\text{hydro}}(t) + P_{\text{biomass}}(t) + P_{\text{storage}}(t)$$

where micro-hydro power is typically modeled as:

$$P_{\text{hydro}} = \rho g Q H \eta$$

with  $Q$  being flow rate,  $H$  hydraulic head, and  $\eta$  system efficiency.

The sustainability of these MHPPs, however, is increasingly threatened by changing precipitation patterns and glacial melt associated with climate change (Khan, 2025), which directly impacts  $Q(t)$  and introduces long-term non-stationarity in power availability.

### 3. AI-Driven Optimization and Control Architectures

The operational stability of a hybrid microgrid is defined by its ability to maintain voltage and frequency within strict limits despite the intermittent nature of renewable sources. Traditional control methods often struggle with nonlinear and stochastic behavior of variable renewable energy and residential loads, motivating the adoption of Artificial Intelligence (AI) and metaheuristic optimization algorithms (Aslam et al., 2026; Zahid et al., 2025a).

System control is typically framed as a constrained optimization problem:

$$\min J = \int_0^T (w_1 | \Delta f(t) | + w_2 | \Delta V(t) |) dt$$

where  $\Delta f(t)$  and  $\Delta V(t)$  represent frequency and voltage deviations.

### 3.1 Metaheuristic Algorithms for Load Frequency Control

Metaheuristic techniques such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are widely utilized to tune microgrid controllers. In comparative studies of load frequency control, PSO-optimized PID controllers significantly outperform conventional methods, providing faster settling times and minimal overshoot during load fluctuations (Mirza et al., 2010).

The velocity update in a PSO framework is governed by:

$$\begin{aligned} V_{k,i}(t+1) &= wV_{k,i}(t) + c_1r_1(P_{k,i} - X_{k,i}(t)) \\ &\quad + c_2r_2(G_i - X_{k,i}(t)) \\ &= X_{k,i}(t) + V_{k,i}(t+1) \end{aligned}$$

The optimization objective is typically the Integral Time Absolute Error (ITAE):

$$J = \int_0^T t | e(t) | dt$$

where  $e(t)$  represents system frequency deviation. Research indicates that while GA is effective for global search, PSO offers superior convergence speed and efficiency for real-time applications such as economic dispatch and frequency regulation in Pakistani microgrid environments (Bhutto et al., 2019). Hybrid methods like GOA-PSO-PID further enhance performance, achieving significant overshoot reduction (Zahid et al., 2025b).

### 3.2 Fuzzy Logic and Neural Networks

Fuzzy Logic controllers are particularly adept at handling the uncertainty associated with solar and wind intermittency. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combine the linguistic interpretability of fuzzy logic with the learning capabilities of Artificial Neural Networks (ANN) (Guerra et al., 2024). Type-2 fuzzy controllers represent a further evolution, incorporating a footprint of uncertainty to manage high sensor noise and environmental disturbances prevalent in harsh, dust-prone regions (Salameh et al., 2025).

Table 2. AI Optimization Methods and Performance Metrics for Microgrids

Optimization Method	Application Area	Performance Metric	Scalability
PSO	Voltage and Frequency Control	Fast convergence	High
GA	Harmonic reduction	High accuracy	Moderate
Fuzzy (ANFIS)	MPPT and Stabilization	High robustness	Moderate
ANN	Predictive Diagnostics	Pattern recognition	High
RL (Q-Learning)	Energy Management	Real-time adaptation	Moderate

Multiple AI and metaheuristic techniques have been applied to optimize hybrid microgrid performance under uncertainty. Figure 2

summarizes the major optimization algorithms used in AI-driven microgrid control systems.

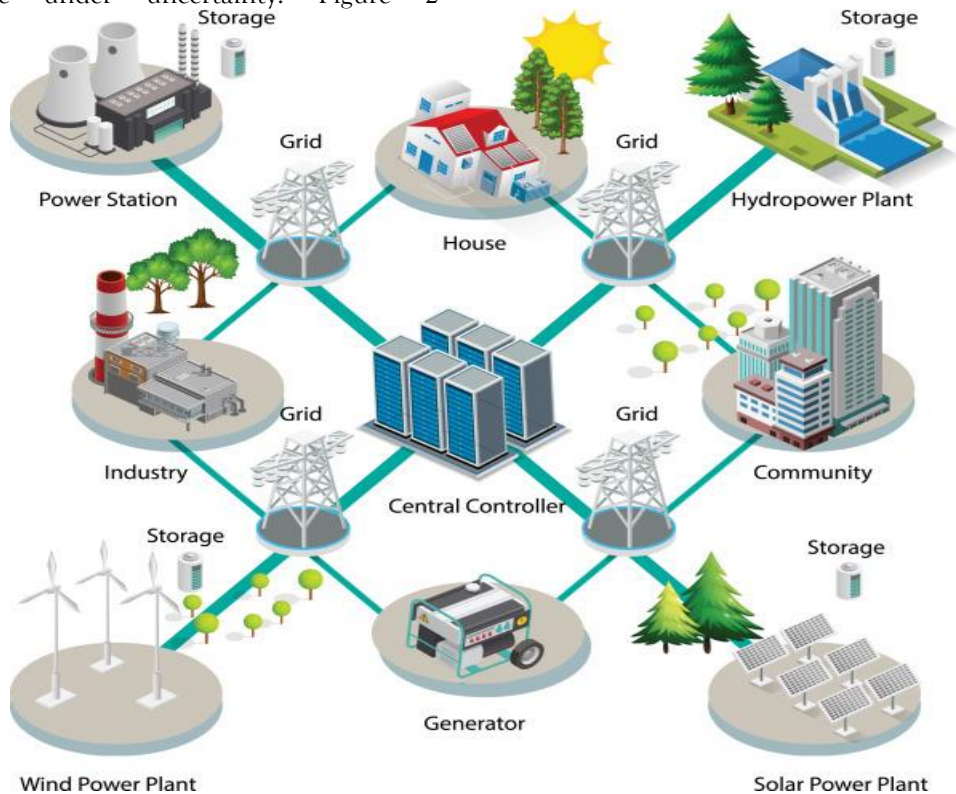


Figure 2: Workflow of AI-Based Energy Management System (EMS)

4. Advanced Load Forecasting and the PRECON Dataset

Accurate load forecasting is the foundation of an efficient microgrid energy management system

(EMS). In Pakistan, residential demand is characterized by extreme variability driven by socioeconomic patterns, seasonal usage of high-power appliances, and the frequent use of

Uninterruptible Power Supplies (UPS) during outages (Nadeem & Arshad, 2019). Advanced forecasting models enable proactive decision-making in microgrid energy management. Figure

3 illustrates the workflow of an AI-based energy management system integrating forecasting, optimization, and dispatch control.

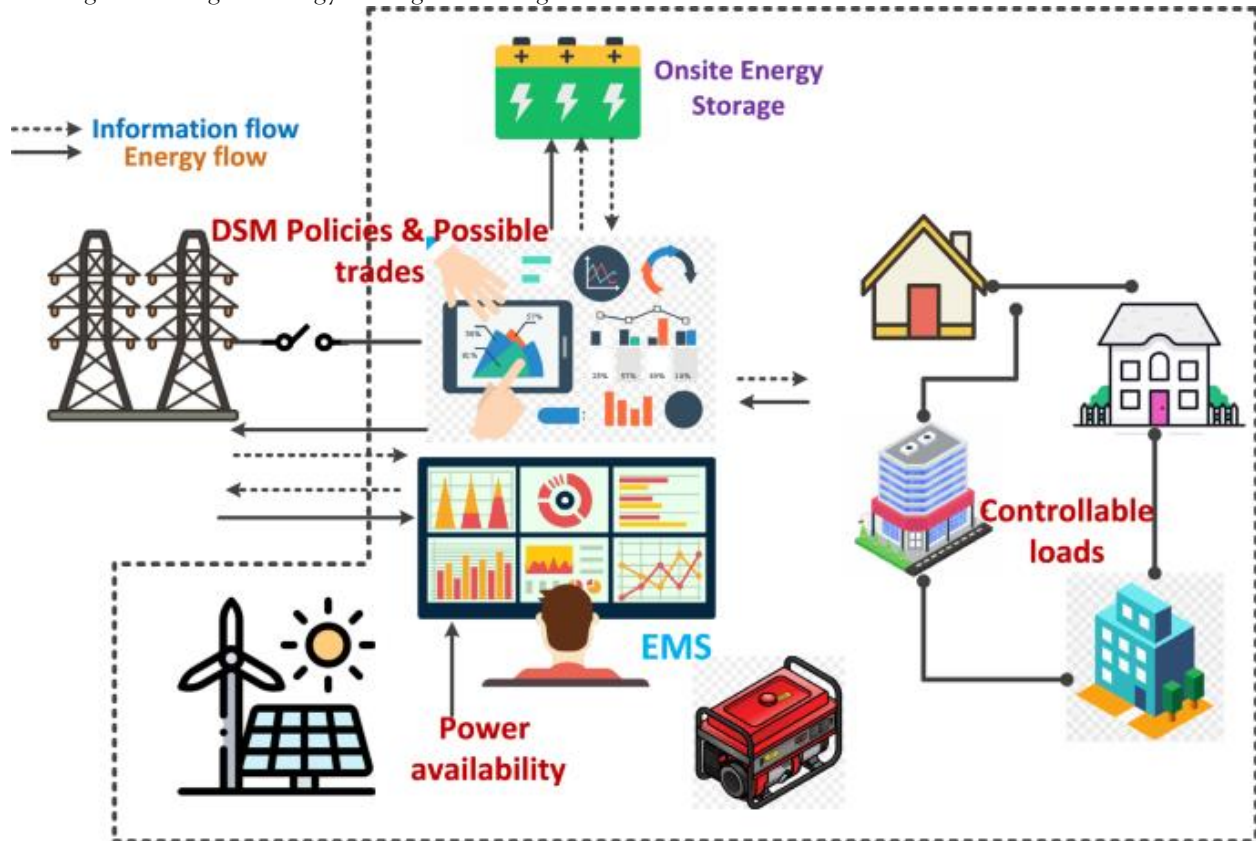


Figure 3: Workflow of AI-Based Energy Management System (EMS)

#### 4.1 The Pakistan Residential Electricity Consumption Dataset

The PRECON dataset, collected over one year from 42 households in Lahore, provides minute-level granularity that is essential for training AI models in a South Asian context (Kaddour, 2023). This dataset captures unique challenges such as concept drift, where consumption patterns evolve due to socioeconomic shifts or weather variability, making it a superior benchmark for local microgrid planning (Zohaib et al., 2026).

Formally, the load time series can be expressed as:

$$y_t = f(x_t) + \epsilon_t$$

where  $y_t$  is electricity demand,  $x_t$  represents exogenous variables (temperature, income proxy, appliance usage), and  $\epsilon_t$  captures stochastic noise. Concept drift implies time-varying data distributions:

$$P_t(y | x) \neq P_{t+\Delta}(y | x)$$

which necessitates adaptive learning models rather than static predictors.

#### 4.2 Hybrid Forecasting Models: PLSTM

The current state-of-the-art for short-term load forecasting in Pakistani microgrids is the Prophet-Long Short-Term Memory (PLSTM) hybrid model. This combines additive time-series decomposition with deep sequence learning.

The forecasting model can be expressed as:

$$\hat{y}_t = g(t) + s(t) + h(t) + \epsilon_t$$

where:

- $g(t)$  = trend component (Prophet)
- $s(t)$  = seasonality
- $h(t)$  = LSTM-based nonlinear residual learning

The LSTM internal memory dynamics are governed by:

$$h_t = \sigma(W_x x_t + W_h h_{t-1} + b)$$

Benchmark tests using the PRECON dataset show that PLSTM achieved a Mean Absolute Percentage Error (MAPE) ranging from 1.58% to 1.90%, significantly outperforming standard LSTM and XGBoost models (Sundaramurthy et al., 2025).

The MAPE metric used for evaluation is defined as:

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{y_t - \hat{y}_t}{y_t} \right| \times 100$$

The implementation of PLSTM-based energy management systems reduces grid imports and improves battery longevity by optimizing dispatch decisions:

$$\min \sum_t C_{grid}(t) - \alpha B_{life}(t)$$

where  $C_{grid}$  is grid energy cost and  $B_{life}$  represents battery degradation penalty.

**Table 3. Performance Comparison of Load Forecasting Models using PRECON Dataset**

Model	MAPE (%)	RMSE	Reduction in Error
PLSTM (Hybrid)	1.58 - 1.90	0.23 - 0.30	Baseline
Standard LSTM	3.50 - 4.36	0.51 - 0.99	12-18%
XGBoost	7.34 - 8.47	1.21 - 1.65	Significant
SARIMA	9.21 - 10.90	High	Poor

### 5. Environmental and Hardware Challenges in Balochistan

The deployment of microgrids in Balochistan faces a harsh environment characterized by extreme heat, airborne dust, and high levels of ultraviolet radiation. These factors directly impact the performance and durability of both PV panels and power electronics (Baloch et al., 2021).

#### 5.1 Thermal Degradation and Cooling Strategies

Solar PV efficiency is inversely proportional to panel temperature. In Pakistan, a rise in temperature results in a drop in output power of approximately 0.4% to 0.5% per degree Celsius. To mitigate these losses, researchers are exploring cooling systems such as thermoelectric panels, which can utilize the temperature gradient between hot panels and cooler water surfaces to enhance efficiency by up to 3.6% (Hasbi et al., 2025).

#### 5.2 Dust Accumulation and Mitigation

The soiling effect from airborne dust is a major obstacle for solar microgrids in desert regions. Studies in Pakistan have shown that optimizing the tilt angle of PV panels seasonally can increase

solar intensity by up to 0.4 kWh/m<sup>2</sup> during the winter (Valasai et al., 2017). Advanced mitigation includes automated dust reduction systems using IoT-enabled microcontrollers (such as the ESP32) that trigger micro-sprinklers when dust concentration reaches critical thresholds, suppressing dust intensity to less than 0.1% (Shakeel et al., 2016).

### 6. Socio-Economic Impact and the Willingness to Pay

For decentralized microgrids to be commercially viable, they must align with the economic realities and energy needs of the local population. A study of off-grid villages in the Multan district provides critical data on the demand for electrification in South Punjab (Khan et al., 2018).

#### 6.1 Demand Analysis and Affordability

The Multan census revealed that despite an average per capita income of only 25 USD per month, there is a strong willingness to pay for reliable energy (Khan et al., 2018). Residents are willing to pay approximately 187 PKR per month for high-quality lighting and nearly double that for the addition of a fan. This indicates that even the

lowest-income segments prioritize energy for health and productivity over traditional kerosene-based alternatives (Naeem et al., 2020).

**Table 4. Residential Willingness to Pay for Electricity Services in Multan**

Service Level	Monthly WTP (PKR)	Key Drivers
Basic Lighting (LED)	187	Health and Education
Lighting and Fan	~370	Comfort and Heat relief
Communal Load	~100	Water pumping and Street lights

**7. Policy Barriers and the NEPRA 2022 Framework**

The National Electric Power Regulatory Authority (NEPRA) introduced the Licensing (Microgrid) Regulations 2022 to address historical hurdles. These regulations provide a streamlined path for developers to electrify unserved areas with capacities up to 5 MW, allowing tariffs to be settled bilaterally between developers and consumers (NEPRA, 2022).

Despite these advancements, the energy sector remains burdened by circular debt and a dearth of technical human resources. AI-driven predictive maintenance methods have emerged as transformative solutions to address these stability issues, with models achieving accuracies between 85% and 95% (Beyer, 2025). Furthermore, researchers advocate for an AI-driven framework to enhance climate resilience in urban and rural infrastructure (Mahadeva & Sindhushree, 2025).

**8. Technical Expertise and Workforce Development**

The operation and maintenance of AI-driven hybrid microgrids require a workforce skilled in modern power electronics and data analytics. Pakistan currently faces a shortage of technical personnel, with most high-skilled roles currently filled by foreign experts (UNDP, 2024). A study by GIZ indicates that Pakistan's renewable energy boom could create 327,000 jobs by 2030, but only if the country can rapidly scale up vocational training to meet emerging demands (GIZ, 2025).

**9. Techno-Economic Performance Case Studies**

A feasibility study in Gwadar compared different configurations for achieving a net-zero energy community (Khan et al., 2023).

**Table 5. Techno-Economic Comparison of Renewable Configurations in Gwadar**

System Model	Configuration	LCOE (USD/kWh)	NPC (USD Million)	Payback (Years)
Model 1	Solar and Battery	0.441	182	6.20
Model 2	Solar, Wind, and Battery	0.320	133	7.79
Model 3	Solar, Wind, and Diesel	0.219	90.7	4.62

While Model 1 is the most environmentally sustainable, Model 3 offers the highest reliability and lowest cost, illustrating the continued necessity of diesel integration in the short term (Elkelawy et al., 2025). Additionally, in District Sanghar, an optimized hybrid system based on solar and wind was identified as the most cost-

effective configuration, providing electricity at RS. 8.78/kWh (Kalghatgi, 2019).

**10. Conclusion**

Decentralized hybrid microgrids, when optimized by AI-driven smart controllers, offer a transformative solution to Pakistan's entrenched rural electrification deficit, where conventional

grid extension remains economically and technically prohibitive. By harnessing advanced algorithms DRL for adaptive decision-making under uncertainty, ANFIS and neural networks for accurate forecasting, and metaheuristics for multi-objective dispatch these systems achieve substantial improvements in cost-effectiveness (15–40% LCOE reduction), renewable utilization (20–50% higher penetration), battery longevity, and reliability compared to rule-based or heuristic-only approaches. The ability to manage stochasticity in solar irradiance, load profiles, and fuel prices while minimizing emissions and operational costs positions AI-optimized microgrids as a cornerstone of climate-resilient, decentralized energy access. In Pakistan's context, where over 40 million people remain unelectrified and rural productivity is constrained by energy poverty, widespread deployment of such systems can catalyze socio-economic upliftment, support productive uses (irrigation, small enterprises), and align with national goals for universal access and renewable integration. Realizing this potential requires overcoming barriers: affordability through subsidies and innovative financing, capacity building for local O&M, data infrastructure for training robust models, and standardization of AI-enabled EMS platforms. Policymakers, utilities, and private developers must prioritize pilot scaling, public-private partnerships, and integration with national electrification programs (e.g., AEDB initiatives) to accelerate adoption. Ultimately, AI-driven optimization transforms hybrid microgrids from niche solutions into a mainstream, sustainable pathway for equitable energy access, rural resilience, and green development in one of the world's most energy-vulnerable emerging economies.

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